

Top  $A_{FB}$  and charge asymmetry in flavor-dependent chiral  $U(1)'$  model

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We study the flavor-dependent chiral  $U(1)'$  model where only the right-handed up-type quarks are charged under  $U(1)'$  and additional Higgs doublets charged with  $U(1)'$  charges are introduced to give proper Yukawa interactions. We find that in some parameter regions, this model is not accommodated only with the top forward-backward asymmetry at the Tevatron, but also with the charge asymmetry at the LHC. At the same time, the cross section for the same-sign top-quark pair production in this model could be below the upper limit at the LHC.

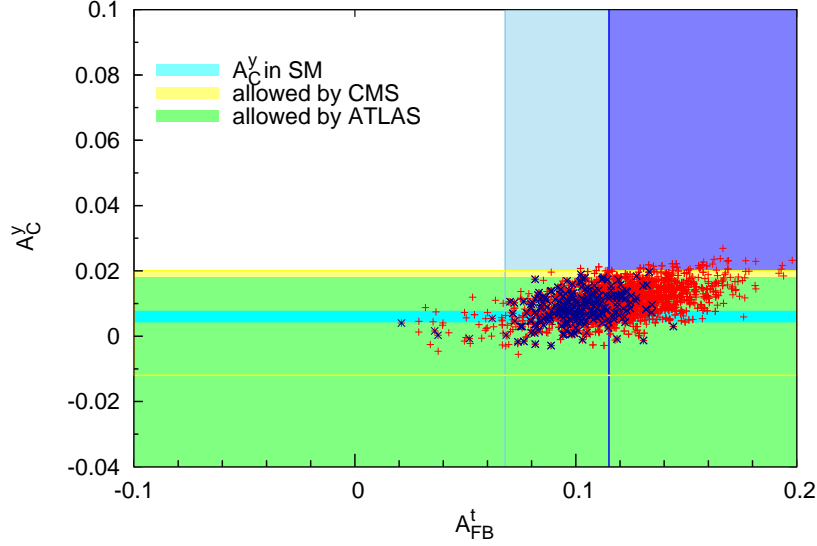
## I. INTRODUCTION

The top forward-backward asymmetry ( $A_{FB}^t$ ) is one of the most interesting observables because there exists discrepancy between theoretical predictions in the standard model (SM) and experimental results at the Tevatron. The most recent measurement for  $A_{FB}^t$  at CDF is  $A_{FB}^t = 0.162 \pm 0.047$  in the lepton+jets channel with a full set of data [1], which is consistent with the previous measurements at CDF and D0 within uncertainties [2]. On the other hand, the SM predictions are between 0.06 and 0.09 [3, 4]. Since the Tevatron collider shut down last year, this discrepancy will remain and the origin of the discrepancy might be unresolved.

If the discrepancy in  $A_{FB}^t$  is generated by new physics, the new physics model would be tested at the LHC. Because the LHC is a symmetric  $pp$  collider,  $A_{FB}^t$  cannot be defined, but the charge asymmetry  $A_C^y$  defined by the difference of numbers of events with the positive and negative  $\Delta|y| = |y_t| - |y_{\bar{t}}|$  divided by their sum, could provide a test ground for nature of the parity violation in the top quark sector. The current values for  $A_C^y$  are  $A_C^y = -0.018 \pm 0.028 \pm 0.023$  at ATLAS [5] and  $A_C^y = 0.004 \pm 0.010 \pm 0.012$  at CMS [6], respectively, which are consistent with the SM prediction  $\sim 0.01$  [3]. Another interesting observable at the LHC is the cross section for the same-sign top-quark pair production,  $\sigma^{tt}$ , which is not allowed in the SM. The current upper bound on  $\sigma^{tt}$  is about 17 pb at CMS [7] and 2 pb or 4 pb at ATLAS depending on the model [8]. Some models which were proposed to account for  $A_{FB}^t$  at the Tevatron, predict large  $A_C^y$  and/or  $\sigma^{tt}$  so that they are already disfavored by present experiments at the LHC.

In this work, we examine the *so-called* chiral  $U(1)'$  model with flavored Higgs doublets and flavor-dependent  $U(1)'$  charge assignment [9]. This model is an extension of a  $Z'$  model with off-flavor-diagonal interactions [10], which is excluded by  $A_C^y$  and  $\sigma^{tt}$  at the LHC. In the Refs. [9], the authors proposed a model with chiral  $U(1)'$  symmetry for the construction of a realistic  $Z'$  model with flavor-off-diagonal couplings, where only the right-handed up-type quarks are charged under  $U(1)'$ , and the  $Z'$  boson is identified as a gauge boson of the  $U(1)'$  symmetry. Then, in order to construct a realistic Yukawa interactions, additional Higgs doublets with  $U(1)'$  charges should be introduced. This is quite similar to the unitarity problem of the  $W_L W_L \rightarrow W_L W_L$  or  $f\bar{f} \rightarrow W_L W_L$  scatterings in the intermediate vector boson model, where the unitarity is recovered by introducing a Higgs doublet. This is also true in any other models with a new spin-1 particle and chiral  $U(1)'$  charges. Finally, new chiral fermions have to be introduced in order to cancel the gauge anomaly. For more details of the chiral  $U(1)'$  models, we refer readers to Refs. [9]. We point out that the simple  $Z'$  model may be disfavored by the experiments at the LHC, but if one considers more complete model, then the extended model could be revived.

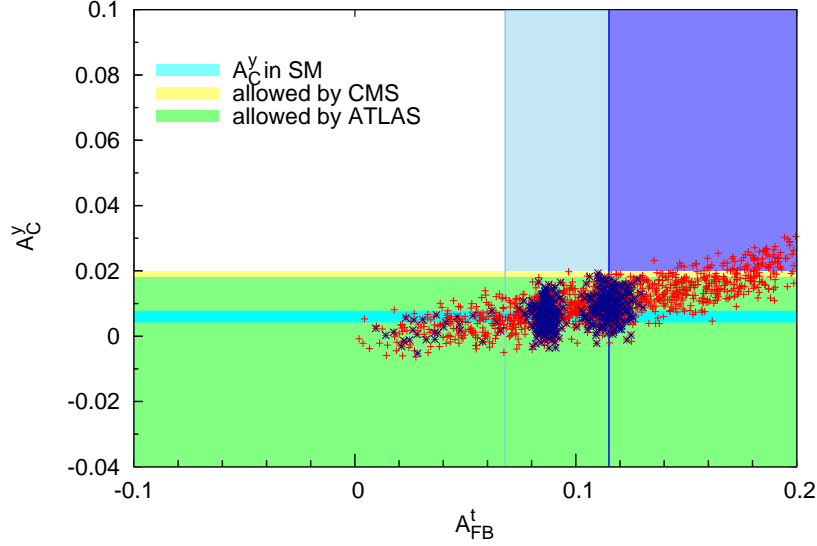
In this proceeding, we consider two scenarios of the chiral  $U(1)'$  model. One is a light  $Z'$  boson case with a neutral scalar Higgs boson  $H$  and a pseudoscalar Higgs boson  $a$ . The other is a light Higgs boson  $h$  case with a heavier  $Z'$  boson, a heavier Higgs boson  $H$ , and a pseudoscalar Higgs boson  $a$ , motivated by the recent observation of an SM-like Higgs boson at the LHC [11]. The other particles newly introduced in the model are assumed to be heavy or have small couplings so that they are decoupled from top physics. Finally, we present a summary of this work.

FIG. 1:  $A_{\text{FB}}^t$  at the Tevatron and  $A_C^y$  at the LHC for  $m_{Z'} = 145$  GeV.

## II. LIGHT $Z'$ BOSON CASE

In this section, we consider a light  $Z'$  boson case with a mass  $m_{Z'} = 145$  GeV. In order to suppress the non-SM decay of the top quark, we require that the Higgs bosons  $H$  and  $a$  are heavier than the top quark. However, this requirement might be inconsistent with the recent observation of an SM-like Higgs boson at the LHC [11] and with non-observation of a Higgs-like signal in a large region between 130 GeV and 600 GeV [12]. In order to accommodate these results, we assume that the  $u$ - $t$ - $h$  coupling, where  $h$  is the lightest Higgs boson, is small enough to be decoupled from the top-quark pair production. In this model, the  $Z'$  boson can contribute to the top-quark pair production through its  $s$ -channel and  $t$ -channel exchanges in the  $u\bar{u} \rightarrow t\bar{t}$  process. While the Higgs bosons contribute to the top-quark pair production only in the  $t$  channel because their Yukawa couplings to light quarks are negligible. We scan the following parameter regions:  $180 \text{ GeV} \leq m_{H,a} \leq 1 \text{ TeV}$ ,  $0.005 \leq \alpha_x \leq 0.012$ ,  $0.5 \leq Y_{tu}^{H,a} \leq 1.5$ , and  $(g_R^u)_{tu}^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ , where  $\alpha_x$  is a  $U(1)'$  gauge coupling and  $Y_{tu}^{H,a}$  are flavor-off-diagonal Yukawa couplings. One can also consider the case where the  $s$ -channel exchange of the  $Z'$  boson is negligible by setting the coupling  $(g_R^u)_{uu} = 0$ , but the numerical results are not so different.

In Fig. 1, we show the scattered plot for  $A_{\text{FB}}^t$  at the Tevatron and  $A_C^y$  at the LHC. The green and yellow regions are consistent with  $A_C^y$  at ATLAS and CMS in the  $1\sigma$  level, respectively. The blue and skyblue regions are consistent with  $A_{\text{FB}}^t$  in the lepton+jets channel at CDF in the  $1\sigma$  and  $2\sigma$  levels, respectively. The red points are in agreement with the cross section for the top-quark pair production at the Tevatron in the  $1\sigma$  level and the blue points are consistent with both the cross section for the top-quark pair production at the Tevatron in the  $1\sigma$  level and the upper bound on the same-sign top-quark pair production at ATLAS. We find that a lot of parameter points can explain all the experiments: the total cross section, the forward-backward asymmetry, the same-sign top-pair production, and the top charge asymmetry, which are considered in this work. We emphasize that the simple  $Z'$  model is excluded by the same-sign top-quark pair production, but in the chiral  $U(1)'$  model, this strong bound could be evaded due to the destructive interference between the  $Z'$  boson and Higgs bosons.

FIG. 2:  $A_{\text{FB}}^t$  at the Tevatron and  $A_C^y$  at the LHC for  $m_h = 125$  GeV.

### III. LIGHT HIGGS BOSON CASE

In this section, we discuss a light Higgs boson case with  $m_h = 125$  GeV, motivated by the recent observation of an SM-Higgs like scalar boson at the LHC [11]. In this case, the  $Z'$  boson and Higgs bosons  $h$ ,  $H$ , and  $a$  contribute to the top-quark pair production. In order to suppress the exotic decay of the top quark into  $h$  and  $u$ , we set the Yukawa coupling of  $h$  to be  $Y_{tu}^h \leq 0.5$  and masses of  $Z'$ ,  $H$ , and  $a$  are larger than the top-quark mass or approximately equal to the top-quark mass. We scan the following parameter regions:  $160 \text{ GeV} \leq m_{Z'} \leq 300 \text{ GeV}$ ,  $180 \text{ GeV} \leq m_{H,a} \leq 1 \text{ TeV}$ ,  $0 \leq \alpha_x \leq 0.025$ ,  $0 \leq Y_{tu}^{H,a} \leq 1.5$  and  $(g_R^u)_{tu}^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ . The mass region of the  $Z'$  boson is taken to avoid the constraint from the  $t\bar{t}$  invariant mass distribution at the LHC. If  $(g_R^u)_{uu} \simeq 0$  and the  $s$ -channel contribution of the  $Z'$  could be ignored, the mass region of the  $Z'$  boson could be enlarged.

In Fig. 2, we show the scattered plot for  $A_{\text{FB}}^t$  at the Tevatron and  $A_C^y$  at the LHC for  $m_h = 125$  GeV. All the legends on the figure are the same as those in Fig. 1. We find that there exist parameter regions which agree with all the experimental constraints considered in this work. We emphasize that in some parameter spaces  $\sigma^{tt}$  is less than 1 pb.

### IV. SUMMARY

The top forward-backward asymmetry at the Tevatron is the only quantity which has deviation from the SM prediction in the top quark sector up to now. A lot of new physics models have been introduced to account for this deviation or it has been analyzed in a model-independent way [13]. Some models have already been disfavored by experiments at the LHC and some new observables are introduced to test the models [13]. In this work, we investigated the chiral  $U(1)'$  model with flavored Higgs doublets and flavor-dependent couplings. Among possible scenarios, we focused on two scenarios: a light  $Z'$  boson case and a light Higgs boson case. We found that both scenarios can be accommodated with the constraints from the same-sign top-quark pair production and the charge asymmetry at the LHC as well as the top forward-backward asymmetry at the Tevatron. In the light  $Z'$  scenario, the same-sign top-quark pair production at the LHC would exclude the scenario if its upper bound becomes less than 1 pb. However, in the light Higgs boson scenario, we could find some parameter regions where the cross section for the same-sign top-quark pair production at the LHC is less than 1 pb.

The chiral  $U(1)'$  model has a lot of new particles except for the  $Z'$  boson and neutral Higgs bosons. The search for exotic particles may constrain our model severely. For example, our model is strongly constrained by search for the charged Higgs boson in the  $b \rightarrow s\gamma$ ,  $B \rightarrow \tau\nu$ , and  $B \rightarrow D^{(*)}\tau\nu$  decays. In order to escape from such constraints, we must assume a quite heavy charged Higgs boson or it is necessary to study our model more carefully by including all the interactions which have been neglected in this work. Search for the dijet resonances would also give strong constraints on the  $Z'$  boson. If the  $s$ -channel contribution is not negligible, the coupling  $(g_R^u)_{uu}$  is constrained by the search for the dijet resonances. However, if the  $s$ -channel contribution can be ignored, we can avoid the constraints from the search for the dijet resonances as well as from the  $t\bar{t}$  invariant mass distribution. In the chiral  $U(1)'$  model, new chiral fermions must be included for the anomaly cancellation. Then, search for the exotic fermions like the 4th generation fermions would also constrain our model. Furthermore, there could be cold dark matter candidates in our model so that the dark matter experiments would give constraints. The most severe constraints arise from the search for the Higgs boson. In this work, we discussed the cases where  $m_h = 125$  GeV, but we did not take into account its branching ratios. If the branching ratios of the SM-like Higgs boson observed at the LHC settle down at the present values, our model will severely be constrained. We emphasize that this study is not complete yet, because there are extra fields which are subdominant in the top-quark production. To a complete study, we need to consider the Higgs phenomenology more carefully.

*Note Added*

While we are finalizing this work, the CMS collaboration has announced much stronger upper limit on the same-sign top-quark pair production:  $\sigma^{tt} \leq 0.39$  pb at 95% confidence level [14]. This bound would exclude the light  $Z'$  boson case, but we note that the light Higgs boson case could still be consistent in a certain parameter space.

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